Optimization for Laser-Propelled Spacecraft at All Launching Times

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In the DE-STAR lab, we propose to use phased laser array with photon propellant in order to achieve significantly higher speed for the spacecraft. During the simulation, the laser is sometimes turned off to avoid cancellation of force or acceleration. However, if we shut off the laser accurately, the duration rises and drops even when the launch time is altered slightly, which makes the real implementation difficult. In this paper, we optimize the algorithm, modifying the craft's orbit to maximize the propelling force. As a result, we stabilize the chaotic outcomes and minimize the time of transit for the craft to reach a target in space.

Keywords: DE-STAR, Directed Energy, Laser Propulsion, Optimizing Orbital Trajectory, Photon Pressure

I. INTRODUCTION

After the New Horizons brought back first high resolution photo of Pluto in July, 2015, topics on space mission became a popular focus of conversations once again. However, in real life, without the futuristic technologies we read in science fictions, the speed of launched spacecrafts and the time span of these projects posed problems for human observations and studies due to the vastness of the universe.

Therefore, in our lab, we propose to use a laser array instead of conventional fuel to propel the craft by shooting the photons onto the sail connected to the craft. The laser system we used is called **DE-STAR**, which stands for **D**irected **E**nergy **S**olar **T**argeting **A**steroids and exploRation [**1**]. Indicated by the name, the DE-STAR laser is solar powered, so the the energy system is sustainable.

The essential reason for using a laser is the significant potential speed. To measure the scale of efficiency improvements, we compare the simulation results of DE-STAR 4 system (see Figure 1) to real data collected from the Voyager 1 (see Figure 2), which is the spacecraft that has traveled the farthest in universe. By comparing, we see that although it took Voyager 1 roughly 35 years to go beyond the Solar System, a 100kg craft propelled by DE-STAR 4 laser can reach that same distance in roughly 100 days.

Although the progress is impressive, the algorithm is still problematic when reacting to the changes in launch time. While the graph in Figure 3 shows an unpredictable and unclear trend, it reveals that when the launch time is altered slightly, the duration for the craft to arrive at the target distance rises and drops sharply, and without a perceivable pattern. However, pattern in the graph do exist in the graph but difficult to evaluate due to the interference of noise, which we plan to eliminate through the process of optimization.

This interferences is the result of the uncontrollable differences between the positions of the craft and the laser at the resonance point. The two objects are constantly at a significant distance from each other but are in an optimal position when they converge at the overlap region of their orbits (see red arrow in Figure 4).

Simulation results for DE-STAR

Craft Mass (kg)	1	10	10^2	10^3	10^4
Days to 1 AU	0.3	1	3	10	30
Speed Compare to c	**4%**	**1.2%**	**0.4%**	**0.15%**	**0.05%**

FIG. 1. The simulation results of craft propelled by DE-STAR 4, one of the DE-STAR system with 10km optic.

Data on the Voyager 1

Launch Time	Out of Solar System	Speed	Speed Compare to c
1977	2012	17km/s	**0.006%**

FIG. 2. Time and speed of the Voyager 1[**2**], one propelled by conventional fuel.

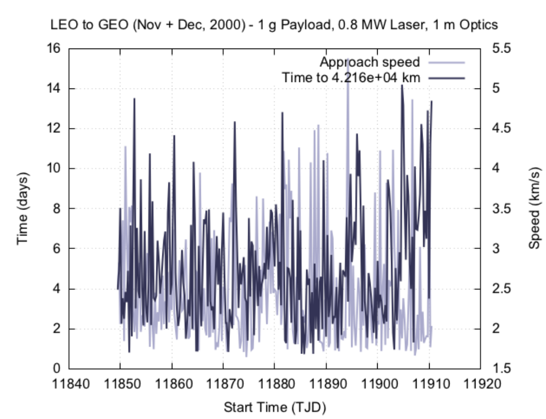

FIG. 3. Change of duration and approach speed over launch time of a 1g craft propelled by a 1m optic laser with 0.8MW power.

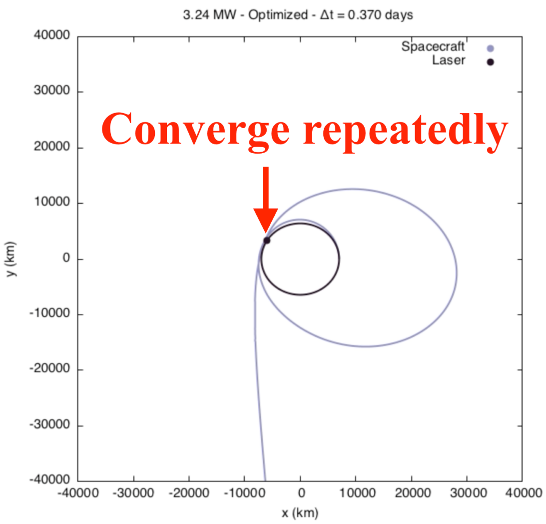

FIG. 4. Optimization caused by convergence at resonance point with a 1g craft propelled by a 3.24MW laser.

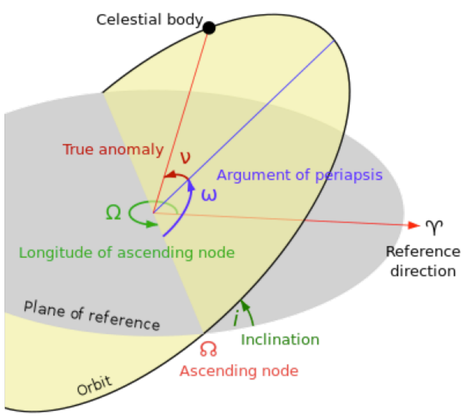

FIG. 5. The Keplerian Orbital Elements Diagram [**3**]

II. DECIDING BEST TIMING

To optimize the orbital trajectories, we add a new section of code to our original algorithm. It functions as the optimizer. In this part, the optimizer reconsiders the time to turn off laser when it senses that the laser will be off for all time before the craft arrived at the resonance. Consequently, when the laser shut-off time is altered, the speed of the craft will be altered upon that, and the duration for the craft to reach the resonance is modified as well.

This duration is more critical in our algorithm since it acts as an indicator to check if the laser and the craft can reach the resonance at the same time.

$$\Delta T_{craft} = nP + \Delta T_{laser} \tag{1}$$

Equation (1) is essentially what the optimizer is doing as lines of codes. The left side of equation (1) represent the time $\boldsymbol{\Delta T_{craft}}$ that the craft need to get to the resonance point, and the right side is the laser counterpart. However, as demonstrated in Figure 4, the craft trajectory is longer than that of the laser. Therefore, on the right side of the equation (1), $\boldsymbol{\Delta T_{laser}}$ stands only for the duration for the laser to hit the resonance the first time. Normally, the craft will not be around at resonance during the laser's first hit at it, so the laser keeps orbiting the Earth for **n** more periods, each one taking **P** amount of duration.

III. OPTIMIZER'S DECISION

The optimizer decides the best time to turn off laser based on its calculation and decision. In doing that, we need to set the orbit to our reference plane so the later processing can be easier since the Earth is the origin in the reference coordinate plane.

We rotate the orbit along x, y, and z axises to reduce three orbital elements (see Figure 5 for visual expression):

1. Inclination
2. Longitude of ascending node
3. Argument of perigee

These three angles can be found by using predefined function in the algorithm when we input the current position and velocity along with time in JDE units.

After the orbit is set to the reference plane, we calculate the true anomaly directly through the object's position, using generic elementary numeric function arctan. However, it turns out that the perigees of the craft and the laser are not exactly the same (the x-axis is pointing to perigee of each orbit) in a way that we need to adjust the true anomaly of the laser with respect to that of the craft since the craft is eventually the object we care about.

After this adjustment, the x-axises point to a same direction that any position has a same coordinate in either the laser or the craft plane (symbol reference see Figure 5):

$$\text{Adjusted Laser True Anomaly} = \boldsymbol{\theta}\text{laser} - [(\boldsymbol{\omega}\text{laser} + \boldsymbol{\Omega}\text{laser}) - (\boldsymbol{\omega}\text{craft} + \boldsymbol{\Omega}\text{craft})]$$

Before getting to $\boldsymbol{\Delta T_{craft}}$ and $\boldsymbol{\Delta T_{laser}}$ in equation (1), two more elements are required. We find them by using following equations:

$$E = \arctan\sqrt{\frac{e+\cos\theta}{(1-e^2)\times\sin\theta}} \tag{2}$$

In equation (2), **e** represents the orbit eccentricity and **θ** represents the true anomaly. We use this to find **E**, the eccentric anomaly.

$$M = E - e\sin E \tag{3}$$

E and **e** in equation (3) represents the same value as those in equation (2). To find mean anomaly value **M**, we plug equation (2) into equation (3) to find mean anomaly.

Due to the property of mean anomaly, we get the percentage of time used in one period. Subtracting that value from 1, we have the percentage of either of the ***ΔT***, from equation (1), in one period ready. When multiply the resulting percentage with orbit period, we have ***ΔT***.

All the elements in equation (1) are then ready except for **n**, which stands for the number of periods that the laser orbits before the craft comes back. While the left side of equation (1) is then a fixed value, we use a loop to find which **n** value returns a closest right side value to the left side value.

With **n** value found, the process comes to an end where the optimizer starts to decide which is the best time to turn off laser. We provide the optimizer with all the previous positions and velocities in current orbit and it runs a loop to pick one of them that will allow the left and right side of equation (1) have the smallest difference, or even equal, although the chance is infinitesimal. In this process, **n** value is already found in previous calculation, and thus is a fixed constant during the loop.

At the end, the best position and velocity are found, so the system will match these two vectors with time, and terminate the optimizer after returning the best time to turn off laser.

IV. INSTRUCTIONS FOR THE OPTIMIZER

Although the optimizer is installed successfully in the algorithm and should function as expected, there is a last part of the optimization process. Using the optimizer and considering cost of speed is also critical in using the optimizer. It seems clear that using the optimizer every single time before the laser-off will backfire, because too many adjustments are added onto the original orbit. Therefore, prior to the final simulation results, we set up so far 6 inputs adjustable for users. They function to instruct the optimizer how close the two objects should be at the resonance point decided by the optimizer, how far back/ forward the optimizer is allowed to choose its best point, when is it allowed to work, how much it should be shifted in order to work the best with the laser, and how much the orbit is allowed to be modified.

With all these added as inputs, the optimizer works better that the users can modify the simulation orbit according to distinctive purposes.

V. RESULTING SIMULATIONS

Graphic

As an outcome, our optimizer provides improvements to the efficiency of the orbital trajectories. Examining the left column of Figure 6, which are graphs generated by the previous algorithm, and comparing them with those in the right column of Figure 6, simulation results after the installation of our optimizer**,** there are three major progress in the orbits:

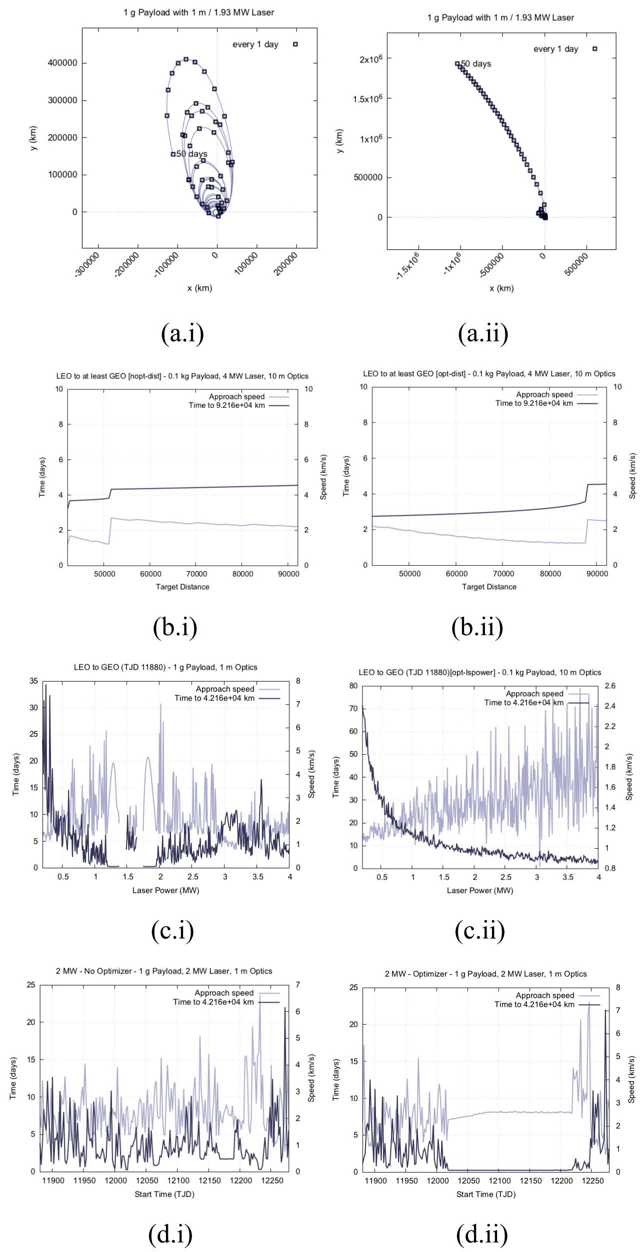

FIG. 6. Simulation results with left column being unoptimized cases and the right one being the optimized: (a) Orbital trajectory of a 10g craft propelled by a 1.93 MW laser with 1m optic in 50 days after launching. (b) Durations and approach speeds of a 0.1kg craft propelled by a 4MW laser with 10m optic when target distance increases from LEO to GEO and above. (c) Durations and approach speeds of a 1g craft going from LEO to GEO propelled by a 1m optic laser when laser power increases from 1 - 4MW. (d) Change in durations and approach speeds over change of starting time of a 1g craft propelled by 2MW laser with 1m optics.

1. It forces the craft into a new orbit when situations are allowed, so the craft can be sent accurately out to escape the Earth's gravity (see Figure 6.a).

2. When the target distance extends to a certain degree, the optimization starts to stabilize and shows a constant advantage over the previous algorithm (see Figure 6.b).
3. The utilization of optimizer smooths out the effect of laser power on duration, so when the laser power increases, the duration shows a exponential-similar decrease (see Figure 6.c).
4. Even though the starting time changes, there is a long period of formality such as the flat part of the graph in Figure 6 d.ii., while the unoptimized counterpart shows chaos in the left column.

Summarizing the 4 improvements on the orbital trajectory, we find that the installed optimizer successfully stabilize the originally outcome when launch time varies.

Data

To understand how much out optimizer can improve the trajectory each time the craft is launched, we use the definition of standard deviation to interpret the status of the before and after trajectories resulted from simulation.

In Figure 7, z value refers to the improvements in the optimized orbits. Comparing the orbit with and without the optimizer in every short amount of time before the craft reaches target distance, the z value shows that over 68% of the time that the optimizer improves the orbit when $z \geq 1$, and over 95% of the time when $z \geq 2$. In the three cases shown in Figure 7, the trend of improvement shows that we have a great amount of confidence in our optimizer that it can effectively optimize the orbital trajectory of the craft at all launch time.

VI. FUTURE DEVELOPMENTS

Due to a variety of unknown matters and uncertainties out in the universe, simulation results of space mission in first stage of preparation often turn out chaotic and unfriendly to real implementation. The advantage of our optimizer in this stage is the stabilization added to the chaos, cleaning away unpredictable noises when reaching to the optimizations. Comparing to the previous algorithm, the newly developed optimizer effectively provide convergence for the laser and the craft at the resonance point through calculation, so the optimization became not so dependent and sensitive upon slight changes in launch time.

However, there are still noises, and also in some cases, without optimizer returns better results than that given by the presence of the optimizer. Such as the area where the red arrows are pointing to in Figure 8, without the optimizer, the pointed part shows a relatively stable and flat pattern where durations are kept low, and in the same area in the right graph with optimizer, the pointed area shows relatively higher chaos and unpredictable trend.

Thus to conclude, our level of confidence in whether our optimizer will provide a better result is still uncertain.This means that the possibility of getting worse results with the optimizer still exists in the simulation, and we are not yet able to tell when will that occur. As an extension of designing and installing the optimizer, the proper implementation of the optimizer will be our future topic. Currently, we have set up a list of inputs that will help us control the performance of the optimizer, and that list will probably be extended in the future. Also, to find out this reason of ineffectiveness of the optimizer, we will first use statistic analysis to find out whether or how much the trajectory is optimized and improved. From that, we should be able to start seeing some pattern and work on perfecting our optimizer.

Improvement Calculation

	1.93MW laser	2MW laser	3MW laser
Unoptimized Mean Time	3.50 days	3.68 days	1.56 days
Optimized Mean Time	2.08 days	1.86 days	1.19 days
z value	4.84	2.01	8.98

FIG. 7. Improvements in orbital trajectories of a craft propelled by different lasers. Mean time calculated based on time of transit that a 1g craft needs to go from LEO to GEO when launched at various times.

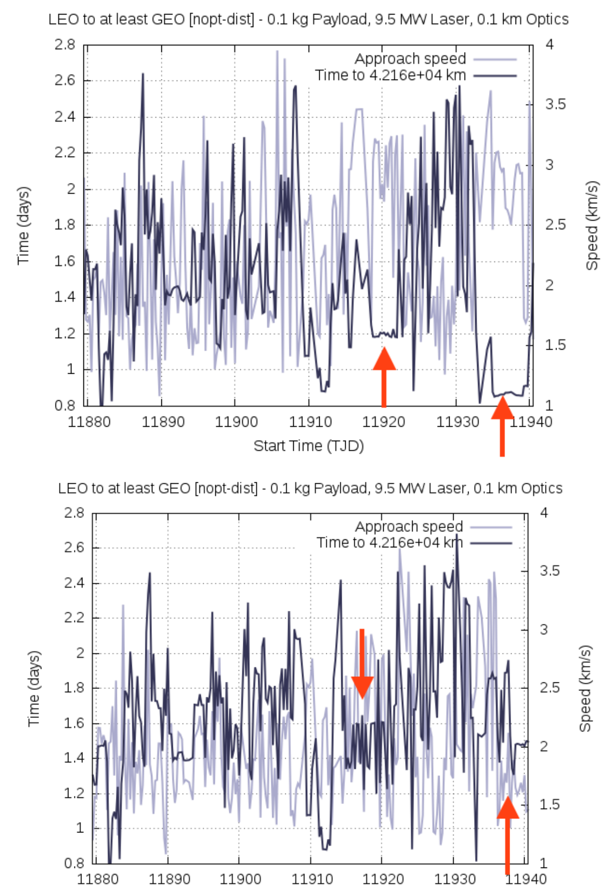

FIG. 8. Change of duration and approach speed of a 0.1kg craft propelled by 9.5MW laser with 0.1km optics over changes in launch time. Top: without optimizer. Bottom: with optimizer.

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